

IAP20 Rec'd PCT/PTO 14 DEC 2005

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"A method for the location of mobile terminals, related systems and terminal, computer program products therefor"

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Field of the invention

The present invention relates to techniques for the location of mobile units or terminals.

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Description of the related art

A number of techniques are known in the art that permit the location of mobile units in a given area; exemplary of such a system is the satellite-based positioning system known as the Global Positioning System (GPS).

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Other arrangements exploit the features of certain terrestrial communication systems, such as cellular mobile telecommunication systems, for the location of mobile terminals.

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Most location systems known in the art operate by taking distance measurements with respect to absolute references (or measurements, such as propagation time measurements of radio-frequency signals, that can be related to distance measurements), this approach being common both to satellite-based networks (such as GPS) and "terrestrial" networks.

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Satellite-based location systems are also known that exploit different types of measurements with respect to those considered in the foregoing e.g. the displacement over a given time of the mobile system to be located. These additional measurements have the purpose of improving the accuracy of the location action.

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Statistical filters have also been used in satellite-based location systems and most modern GPS

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receivers include a statistical filter. The related technical literature is quite extensive and includes a high number of scientific publications and patent publications as well.

5 Statistical filters have also been recently proposed for use in terrestrial-based location systems, as witnessed e.g. by EP-A-1 102 398 and EP-A-1 102 399.

Specifically, the arrangement disclosed in EP-A-1 102 398 includes a standard Kalman filter for use in a  
10 mixed satellite-based/terrestrial system. The same arrangement also takes advantage of statistical methods for pre-validating measurements, methods that associate to the measurements (taken individually or jointly) a degree of likelihood and, finally, methods for  
15 computing state innovations.

The arrangement disclosed in EP-A-1 102 399 is a further development over the arrangement described in EP-A-1 102 398 that includes a generalized use of statistical filters. These are used for determining a  
20 sequence of state estimates, these states representing the motion of the object to be located. As regards the Kalman filter, also the "extended" form, for use in non-linear systems, was described. The same document additionally describes the use of statistical filters  
25 within purely terrestrial systems (such as GSM and UMTS) in addition to mixed satellite-terrestrial systems. Also, EP-A-1 102 399 indicates the possibility of dispensing with statistical methods for pre-validating measurements, which are presented as  
30 mandatory in EP-A-1 102 398.

To sum up, the prior art considered in the foregoing broadly and generally discloses the possible use of statistical filters (such as a Kalman filter) in location systems, such a disclosure applying to any  
35 kind of location system whose operation is based on

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measurements derived from terrestrial or satellite-based networks.

The prior art considered in the foregoing leaves however at least two basic problems unsolved.

5       As a first point, statistical filters intrinsically reduce in an optimal way measurement errors and any kind of environment-related error under the assumption that these errors have a well-known statistical distribution (in the case of Kalman filter, errors having a Gaussian distribution with a zero average or mean value are assumed). Experiences show  
10       however that when such arrangement are used in the case of measurements related to terrestrial cellular networks, the performance of the statistical filters is appreciably diminished to the point of making the use  
15       of such statistical filters practically useless.

          Additionally, not unlike satellite-based systems (that may suffer from poor reception or lack of reception, i.e. lack of "visibility" of satellites in  
20       urban canyons and indoor), terrestrial systems may also be adversely affected by phenomena such as multipath or insufficient field strength, these phenomena possibly leading to environments where signals from both satellite-based and terrestrial location systems can be  
25       hardly received or are not received at all.

#### Object and summary of the invention

          The need therefore exists for arrangements that may improve the accuracy of the location action when the above-mentioned standard hypotheses on the statistical  
30       distribution of the measurement errors in statistical filters of conventional type are not met: as explained in the foregoing, this is the case of location effected by means of terrestrial cellular networks.

          The need also exists for arrangements that may  
35       improve the accuracy in the location action in those

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geographical areas where signals from location system -  
of the terrestrial type or the satellite-based type -  
cannot be received satisfactorily.

The object of the present invention is to satisfy  
5 these needs.

According to the present invention, such an object  
is achieved by means of a method having the features  
set forth in the claims that follow. The invention also  
relates to corresponding system and a terminal for use  
10 therein, as well as a computer program product loadable  
in the memory of at least one computer and including  
software code portions for performing the method of the  
invention and/or implementing a terminal according to  
the invention when the product is run on a computer.

15 The invention lends itself to be implemented in a  
variety of different embodiments. These may range from  
a basic arrangement applied to a terrestrial-based  
location system and involving the use of an improved  
statistical filtering process, to more sophisticated  
20 arrangements that use an improved statistical filtering  
process within the framework of a location system using  
both satellite-based and terrestrial-based reference  
elements, in possible combination with additional  
measurements indicative e.g. of the altitude and/or the  
25 displacement (speed, acceleration, and so on.) of the  
mobile terminal. Still another embodiment of the  
invention may provide a location system using both  
satellite-based and terrestrial-based reference  
elements, in combination with additional measurements  
30 and a standard statistical filtering process.

A particularly preferred embodiment of the  
invention is a terminal for use in a vehicle such as a  
motorcar in a possible combination with a GPS receiver.

Essentially, the location system described herein  
35 is based on the use of statistical filters (hereinafter

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reference will be steadily made to a Kalman filter as exemplary of such types of filters or estimators) wherein, differently from the prior art considered in the foregoing, the system states include, in addition to information concerning the motion of the object to be located (for instance its location and speed) a plurality of states that are integrated in the statistical filters in order to optimize the accuracy of the location action. This also in those cases where the measurement errors in the networks have statistical distributions different from those typically hypothesized in the literature.

Preferably, the invention also provides for the optional use of additional measurements with respect to the measurements typically performed in terrestrial and/or satellite-based networks. These additional measurements (such as acceleration measurements) are provided by specific devices and adapted to improve the accuracy of the location action. Use of these additional measurements is established in the area of satellite-based systems, such as a GPS navigator: there, for instance, the location system is provided with information concerning the distance over which the vehicle has traveled and this information, together with cartographic information, makes the location system significantly more accurate in comparison with respect to those situations where only the basic measurements provided in the GPS systems are used.

A preferred embodiment of arrangement disclosed herein provides for measurements to be carried out on signals from one or more base stations in a terrestrial cellular networks (for instance a GSM network) and, optionally, from base stations of a satellite-based system (such as GPS) with the possible optional use of additional information concerning movement of the

system to be tracked as provided, for instance by accelerometers and altimeters.

As indicated, a preferred embodiment of the arrangement shown herein is based on the use of statistical filter such as a Kalman filter adapted to operate also in the case where the measurement errors appearing in the input data to the system have statistical distributions different from those statistical distributions (e.g. a Gaussian distribution with zero mean value) that are currently assumed in standard statistical filter theory.

Such an arrangement is therefore adapted to provide optimal results also in those cases where errors statistical distribution is different from that typically assumed in the known prior art. Exemplary of such a scenario are those situations where location is based on the propagation times of signals from a terrestrial cellular network in an environment affected by multipath propagation effects. Under these circumstances, the measurement error exhibits an average value (mean value) that is higher than zero and, therefore, can not lead to a Gaussian distribution with zero mean value. This is due to multipath being a condition only to increase - and not to reduce - propagation time with respect to the line of sight.

Accordingly, in a preferred embodiment of the arrangement disclosed herein, a fictitious additional state is provided that is adapted to represent such an error, having an higher than zero mean value, that is not usually contemplated in the conventional theory of statistical filters such as the common Kalman filters. In particular, the method according to present invention, enables the use of the kalman statistical filter in a cellular environment.

Moreover, the method enables to obtain good location

results in a very fast time. In fact, due to the use of the Kalman filter with a non zero mean error value, the method guarantees very good performances in terms of both accuracy and speed of convergence (i.e. time  
5 necessary to elaborate the measurements for calculating the position), up to ten time the known solutions.

Brief description of the annexed drawings

The invention will now be described, by way of example only, with reference to the annexed figures of  
10 drawing, wherein:

- figure 1 is a functional diagram depicting operation of a location system as disclosed herein,
- figure 2 is a block diagram disclosing the general arrangement of such a system,
- 15 - figure 3 is a flow chart representative of certain processing steps performed in the location system as disclosed herein, and
- figure 4 schematically represents the possible application of the arrangement shown herein to a motor  
20 vehicle.

Detailed description of preferred embodiments of the invention

By way of introduction to the description of an exemplary embodiment of the arrangement disclosed  
25 herein, some basic principles of Kalman filter theory will be briefly summarised here. This is done by referring specifically to the arrangement known as the so-called "Extended Kalman Filter" or, briefly, EKF.

Once again, it is worth recalling that reference to  
30 a Kalman filter is in no way intended to limit the scope of the invention that in fact encompasses use of any statistical filter or predictor of a known type.

For the sake of simplicity, it will be assumed that the mobile terminal to be located is still (i.e. not in  
35 motion), and the additional measurement provided to the

location system is the altitude above sea level of the terminal. The measurements provided by the terrestrial cellular networks are typically the propagation times of the radio frequency signals.

- 5 According to basic EKF theory, such a scenario can be described as follows.

$$\begin{cases} \bar{x}_{k+1} = f(\bar{x}_k) + \bar{w}_k \\ \bar{y}_k = h(\bar{x}_k) + \bar{e}_k \\ g(\bar{x}_k) = \bar{d}_k \end{cases} \quad (1)$$

- 10 The vector  $\bar{x}$  is the unknown variable of the problem that is to be evaluated via the Kalman iterative process.

In the present case, the vector  $\bar{x}$  includes:

- the three coordinates  $x, y, z$  of the mobile
- 15 terminal to be located, and, additionally,
- a further state  $t$  that represents the average error of the network measurements  $\bar{y}$  (terrestrial and/or satellite-based) whereby

20  $\bar{x}_k = [x_k \ y_k \ z_k \ t_k]^T$

Since the mobile terminal to be located is assumed to be still then one has  $\bar{x}_k = \bar{x}_{k+1}$  and consequently  $f(\bar{x}_k) = \bar{x}_k$ .

- 25 The vector function  $h(\bar{x}_k)$  describes those measurements that are carried out that, in the case considered, correspond to the propagation times of the radio frequency signal from the base station. The function  $h(\bar{x}_k)$  is comprised of as many functions as
- 30 the measurements available at the  $k$ -th step and, for instance at the  $k$ -th step the  $i$ -th measurement  $y_{i,k}$  will give rise to the equation:



$$y_{i,k} = h_i(\bar{x}_k) + \bar{e}_k = \text{GeometricDistance}(\text{MobileTerminal}_{\text{step}_k}, \text{BaseStation}) + t_k + \bar{e}_k$$

where  $t_k$  describes the non-zero average value of  
 5 the measurement error  $e_k$ .

Therefore, according to a feature of present invention,  $e_k$  is assumed as having a known distribution, i.e. a Gaussian distribution having a zero average value, and  $t_k$  is assumed to be an unknown value to be calculated.

10 In general  $t_k$  represents the non zero average value of the measurements both:

- in case of additive errors;
- in case of multiplicative errors.

The vector function  $g(\bar{x}_k) = d_k$  describes the  
 15 constraints of the location system that render such a system more precise with respect to the case where this additional information were not available. In the instant case  $g(x_k) = z_k$  (that is the altitude coordinate) and  $d_k$  is the altitude above sea level  
 20 provided by means of an altimeter.

Finally,  $\bar{w}_k$  and  $\bar{e}_k$  are two mutually independent Gaussian processes.

The system corresponding to equation (1) above is solved, by resorting to Kalman filter theory, by means  
 25 of the iterative process described by the following system indicated as (2). Specifically, the iterative process starts from the initial condition  $\tilde{x}_0$  and produces a sequence of solutions  $\bar{x}_k$  gradually converging towards the position of the system to be  
 30 located.

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$$\begin{aligned}
 K_k &= AH_k(H_k^T \Sigma_k H_k + R)^{-1} \\
 \hat{x}_{k+1} &= f(\tilde{x}_k + K_k(\tilde{y}_k - h(\tilde{x}_k))) + b(\tilde{u}_k) \\
 \Sigma_{k+1} &= F_k(I - K_k H_k^T) \Sigma_k F_k^T + Q \\
 \tilde{x}_{k+1} &= \hat{x}_{k+1} - \Sigma_{k+1} D^T (D \Sigma_{k+1} D^T)^{-1} (D \hat{x}_{k+1} - p)
 \end{aligned}
 \tag{2}$$

where  $H_k^T$  is the matrix of the partial derivatives of the function  $h(\mathbf{x})$  evaluated for  $\tilde{x} = \hat{x}_k$ ;

5  $F_k$  is the matrix of the partial derivatives of the function  $f(\tilde{x})$  evaluated for  $\tilde{x} = \hat{x}_k$ ; and

$$D = g'(\tilde{x}_{k+1}) \text{ and } p = d - g(\tilde{x}_{k+1}) + g'(\tilde{x}_{k+1})\tilde{x}_{k+1}.$$

10 It will be appreciated that all of the foregoing is well known to those of skill in the art of statistical filters or predictors especially in connection with Kalman filter theory, thereby making it unnecessary to provide a more detailed description herein.

15 The location method considered in the foregoing is better shown in figure 1.

Figure 1 is comprised of functional diagram that is essentially similar to a flow chart identifying four basic phases comprising the method described herein, such basic phases being designated 1 to 4, respectively.

The phase designated 1 essentially involves extracting the information necessary for location purposes from:

- 25
- a terrestrial cellular system T,
  - a satellite-based system S, and
  - other source of location information, generally designated A.

Such additional measurement sources may include the altitude information (i.e. the coordinate z) and/or (especially for applications in the automotive field)

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measurements indicative of the distance travelled by a motorcar over a given time interval.

It will be appreciated that the criteria and methods for obtaining those signals are well known in the art, thus making it unnecessary to provide a detailed description herein.

Reference 2 designates as a whole the phase wherein the initial conditions are estimated. Again, this occurs on the basis of methods that are well known in the art and, as such, are not significant for the purpose of understanding the invention.

The further phase 3 includes those steps that comprise the processing engine proper for calculating the position at the k-th step. Essentially, the phase designated 3 comprises the statistic filter processing and can essentially be regarded as including:

- a first step 100 wherein the covariance matrixes and the system gain are updated,
- a second step 102 wherein the system states are updated, and
- a step 104 where the system states are filtered.

Finally, the phase designated 4 includes those steps that make the results of the location action available to the client (i.e. the party requesting the location information).

These results may be in the form of "raw" position information for tracking on a geographic identification system (GIS) or any other forms of position display.

In the block diagram of figure 2, a mobile terminal MS is shown representing the mobile terminal to be localized.

The mobile terminal MS is adapted to receive signals from a plurality of satellites Sat1,..., Satm together with additional information for improving the accuracy of location action performed by the system.

To that purpose, the terminal MS includes a software module designated PCF1, essentially intended to implement a positioning calculation function according to the invention.

5       The satellites designated Sat1,...., Satm transmit radio frequency signals adapted to permit to the mobile terminal MS to compute the distances of the mobile terminal MS to the various satellites.

10       The radio-frequency (radioelectric) signals transmitted from the satellites also include information required for exactly determining the positions of the satellite themselves. This occurs according to well-known criteria currently adopted in GPS systems of commercial type or other satellite  
15 systems.

      References SRB1,....SRBn designate a number of base stations (SRB or BTS) included in a terrestrial cellular communications system CA.

20       Those base stations transmit over the area covered by the network CA radio-frequency signals that permit the mobile terminal MS to compute the distance with respect to various base stations.

      This occurs by means of power measurements (e.g. by measuring the signal power received at the mobile  
25 terminal from the various base stations) or by measurements of entities such as timing advance (TA), round trip time (RTT), observed time differences (OTD), observed time differences of arrival (OTDOA) and any other type of measurements currently available in a  
30 terrestrial mobile radio network for locating the mobile terminal MS based on a method generally known in the art.

      Of course, the positions of the base stations are known a priori and stored in a geographical data base.

An altimeter system provides data indicative of the altitude above the sea level of the mobile terminal MS to be localized.

The altimeter in question is exemplary of an additional measurement system (AMS) that may provide additional information adapted to render the location action significantly more precise. This in respect of both the altitude coordinate  $z$  (which, of course, is an entity known very precisely, and not estimated) and the "plane" coordinates  $x$  and  $y$ , namely latitude and longitude.

Reference MLC designates as a whole a mobile location center adapted to cooperate with the mobile terminal MS via the mobile network CA.

The MLC system includes a bus-like arrangement of sub systems acting under the coordination of a management system designated SM.

The subsystems typically include a gateway GW towards the IP (Internet Protocol) world, thus permitting a remote user U to request and obtain the position of the mobile terminal MS. Such a function may be of interest for the delivery of so-called location based services (LBS) to the user of mobile terminal MS.

Reference PCF2 designates a positioning calculating function substantially duplicating the module PCF1 present in the mobile terminal MS for location purposes.

Reference MCG designates a communication management module currently associated with the mobile network CA. Essentially, the module MCG performs, for example, a number of tasks such as:

- set-up the suitable communication (i.e. SMS, GPRS) between the user U and the terminal MS;
- transmit information through the network.

Finally, reference AB denotes an accounting and billing module.

The flow chart of figure 3 depicts the various steps that are carried out when the user in possession of mobile terminal MS decides, in a start step 110, to activate the location procedure.

As a first step, designated 112, the terminal MS performs the various measurements on the radioelectric signals received both from the satellite network and from the terrestrial cellular network.

In a subsequent step 114, the mobile terminal MS collects the altitude information from the AMS system.

Subsequently, the terminal MS transmits, via the module MCG, all the measurements performed. This occurs in a step 116 that also leads the module MCG, after verifying the identity of the user via the SM and AB modules, to transfer the information received to the module PCF2.

In a step 118, the module PCF2 calculates the position of the mobile terminal MS and, via the module SM, re-transmits the results to the mobile terminal by possibly informing the billing module AB.

At that point, in a step 120, the terminal MS may collect new measurements and therefore prompt an iterative process leading to the terminal MS being "tracked" over time by reporting the position information just computed to the user.

When the location function is satisfactorily completed, the system evolves to an end step 122.

In an alternative, at present preferred embodiment to the arrangement shown herein, the position of the mobile terminal is computed (step 116) with the mobile terminal itself, by exploiting the processing capability of the respective module designated PCF1.

Any mobile telecommunication terminal provided with a certain degree of signal processing availability (such as mobile terminals of the so-called "Smartphone" type) are equipped with sufficient data processing power to perform such processing tasks.

If such a solution is adopted, the MLC system plays a support role by providing the mobile terminal MS with information including e.g. the positions of the base stations of the cellular network CA. Communication takes places via the MLC modules.

Still alternatively, the location action may not be prompted by the user in possession of the terminal MS but rather by a remote user U connected via the IP network.

In that case, the module GW permits such a remote user to access the location system after verifying its identity thereof via the module AB. At this point, acting under the supervision of the module SM, the system MLC sends the request to perform the location action and report all the measurements available to the mobile system MS by activating either of the functions PCF1 or PCF2 as soon as these measurements are received.

The results of location are then reported to the remote user U while simultaneously activating the billing module AB.

Such a location action prompted by a remote user U can be made subservient to a specific authorization being granted positively by the mobile terminal MS e.g. by the user pressing a given key in that terminal. Still otherwise, for privacy purposes, the mobile terminal MS may notify the system MLC that no request for location prompted by a remote user U should be processed by the system.

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As previously indicated, several additional variants of the basic arrangement described previously can be easily conceived.

For instance a first variant provides for the possibility of dispensing with any measurements carried with the support of the satellite-based system. Essentially, this variant corresponds to deleting from the basic layout of figure 1 the block designated S, while leaving in place both blocks designated T (measurement from the terrestrial network) and A (other measurements system).

Another variant dispenses also with the information provided by the additional measurements designated A. In that case, location is performed on the basis of the sole information derived from the terrestrial system T.

Those of skill in the art will appreciate that those exemplified in the foregoing are just two of the many possible variants.

Any of the arrangements disclosed herein can be advantageously adopted in an automotive scenario as schematically shown in figure 4. In that figure, reference M designates a vehicle such as a motorcar equipped with a standard GPS receiver 201 as well as a terminal for terrestrial cellular mobile network 202. The vehicle M is also equipped with measurement system 203 adapted for measurement e.g. the distance travelled by the vehicle M over a given interval of time. All the elements considered in the foregoing are preferably connected via a bus arrangement. This is preferably in the form of a so-called "CAN BUS" characterized a high degree of robustness to environment noise.

Reference 204 designates a processing module essentially corresponding to the module designated PCF1 in figure 2. Such a module calculates the position of the motor vehicle M by resorting to the method



considered in the foregoing based on the use of  
statistic filters. Finally, reference 205 designates a  
system for managing location information preferably  
including displayed unit adapted for presenting the  
5 result of the location action to the driver of the  
motor vehicle M.

Of course, without prejudice to the underlying  
principles of the invention, the details and  
embodiments may vary, also significantly, with respect  
10 to what has been described by way of example only,  
without departing from the scope of the invention as  
defined by the annexed claims.

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